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14. ABSTRACT

As proposed, we upgraded the system console on an existing Bruker Instruments, 14 T nuclear magnetic resonance (NMR) spectrometer to enable an improved implementation of type II quantum computers (TTQC). This upgrade is fully functional and has permitted our NMR studies to be moved to higher strength magnetic fields for better sensitivity and spectral dispersion. The TTQC experiments continue in collaboration with Dr. J. Yepez of the Air Force Research Laboratory.
We have completed studies of the I-D dynamics of the diffusion equation and the Burger's equation with various viscosity. We have nearly completed additional studies showing both the scaling of errors in TTQC and a new novel mapping to reciprocal space lattices. The latter is hoped to be a first step toward running the TTQC with a closed feedback loop. The closed loop computations will permit continuous quantum computation in a lattice gas architecture.

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Final Report

Nuclear Magnetic Resonance Spectrometer Console Upgrade for a Type II Quantum Computer

F49620-02-1-0250

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As proposed, we upgraded the system console on an existing Bruker Instruments, 14 T nuclear magnetic resonance (NMR) spectrometer to enable an improved implementation of type-II quantum computers (TTQC). This upgrade is fully functional and has permitted our NMR studies to be moved to higher strength magnetic fields for better sensitivity and spectral dispersion. The TTQC experiments continue in collaboration with Dr. J. Yepez of the Air Force Research Laboratory.

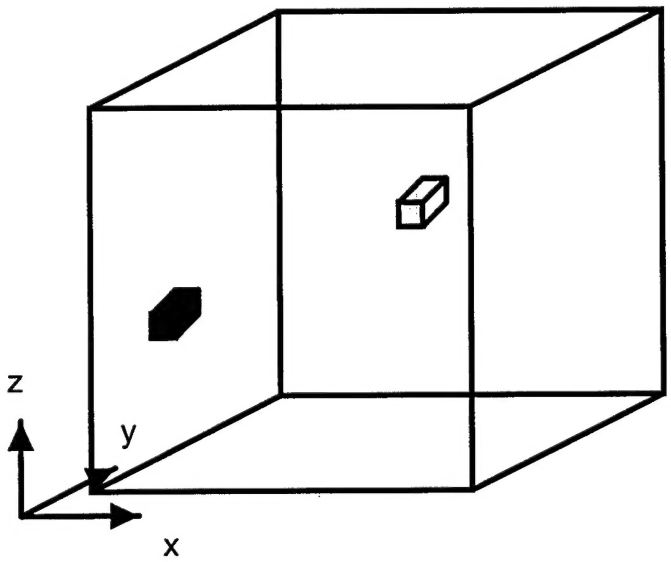
We have completed studies of the 1-D dynamics of the diffusion equation and the Burger's equation with various viscosity. We have nearly completed additional studies showing both the scaling of errors in TTQC and a new novel mapping to reciprocal space lattices. The latter is hoped to be a first step toward running the TTQC with a closed feedback loop. The closed loop computations will permit continuous quantum computation in a lattice gas architecture.

Description of new instrumentation

An NMR console is essentially a set of programmable radio-frequency transceivers. The new console for the 14 T magnet is the latest Avance series from Bruker Biospin, Inc. The console permits complex modulations of RF power with excellent stability and reproducibility. The console also includes a broadband, linear RF receiver (and 2 MHz digitizer) so that the spin's response can be accurately monitored. In addition, the spectrometer console runs a series of simultaneous background tasks, controlling the time sequenced magnetic field gradients, along with the strength and homogeneity of the magnet field and finely controlling the temperature of the sample. All of these must be precisely, and linearly controlled to accurately implement a TTQC via NMR. The obsolete console that was on the 14 T magnet did not have the flexibility, stability or precision for useful quantum computing studies.

Introduction to the TTQC applications of the new device:

The type II quantum computer is an array of small (3-9 qubit) quantum information processors (QIP) with classical interconnections. We have built on our experience with NMR QIP and with NMR imaging to integrate these two fields and to implement an NMR-based TTQC. Here the spin dynamics in time dependent magnetic field gradients are used to spatially separate individual quantum processors, and each is then treated as a separate and distinct QIP.



The above is a schematic representation of the lattice-gas quantum computer. The TTQC is a large continuous sample of an organic liquid similar to that which would make up an NMR liquid state QIP. This large sample is broken into separately addressable QIP by the action of magnetic field gradients along the x, y, & z directions. Methods are well known to selectively excite any desired region of the sample, indeed we have demonstrated (1, 2) that through a series of simultaneously applied shaped RF and gradient pulses we can in parallel apply different unitary operations to any set of regions in the larger sample. It is this parallel addressing of the system which permits writing separate information simultaneously to each individual QIP, a key element of a TTQC. Of course by leaving the gradients off, then any propagator can also be applied across the entire sample in one step.

The gradients also play an important role in data readout since they provide a separation of the NMR resonance frequencies for each individual QIP, thus permitting a linear array of states to be read in parallel.

Our first studies were of the 1-D diffusion equation. This has been published, below we outline some of our as yet unpublished studies of the Burger's equation. Since the Burger's equation can generate a sharp feature in the mass density it is a more challenging dynamic to simulate on NMR TTQC. This indeed was our motivation in choosing the equation. In the diffusion equation experimental imperfects and approximations made in the implementation tend to blur the resultant mass density. Since the mass density should correctly evolve to a gaussian, it was difficult to distinguish if the final gaussian result arose due to correct running of the TTQC or due to a blurring from the errors.

We have studied two implementations of the Burger's equation with different viscosity. For the low viscosity simulation, the collision operator $\hat{C}$ is the square root of NOT gate,

$$\hat{C} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1/\sqrt{2} & 1/\sqrt{2} & 0 \\ 0 & -1/\sqrt{2} & 1/\sqrt{2} & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}.$$

Expressed in terms of the Pauli operators,

$$\hat{C} = \exp\left[i \frac{\pi}{8} \left(\sigma_x^1 \sigma_y^2 - \sigma_y^1 \sigma_x^2 \right) \right].$$

The exponential can be implemented by realizing that it can be expanded as scalar coupling ($\sigma_z\sigma_z$) sandwiched by single-spin rotations as shown in the pulse sequence of figure 1.

In the high viscosity case, the collision operator is,

$$\hat{C} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 0.8 & 0.6 & 0 \\ 0 & -0.6 & 0.8 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix},$$

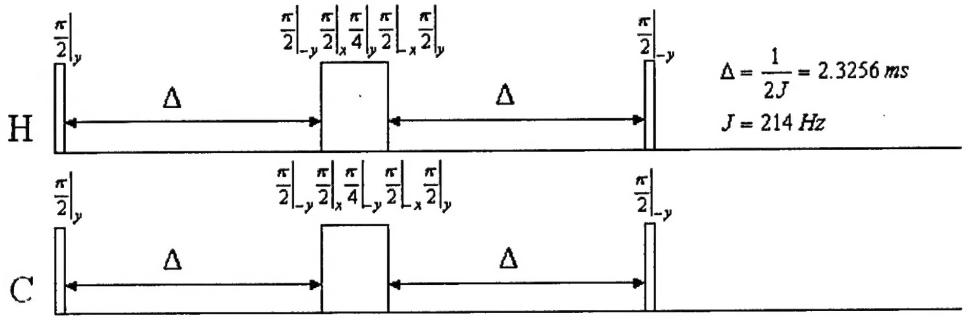
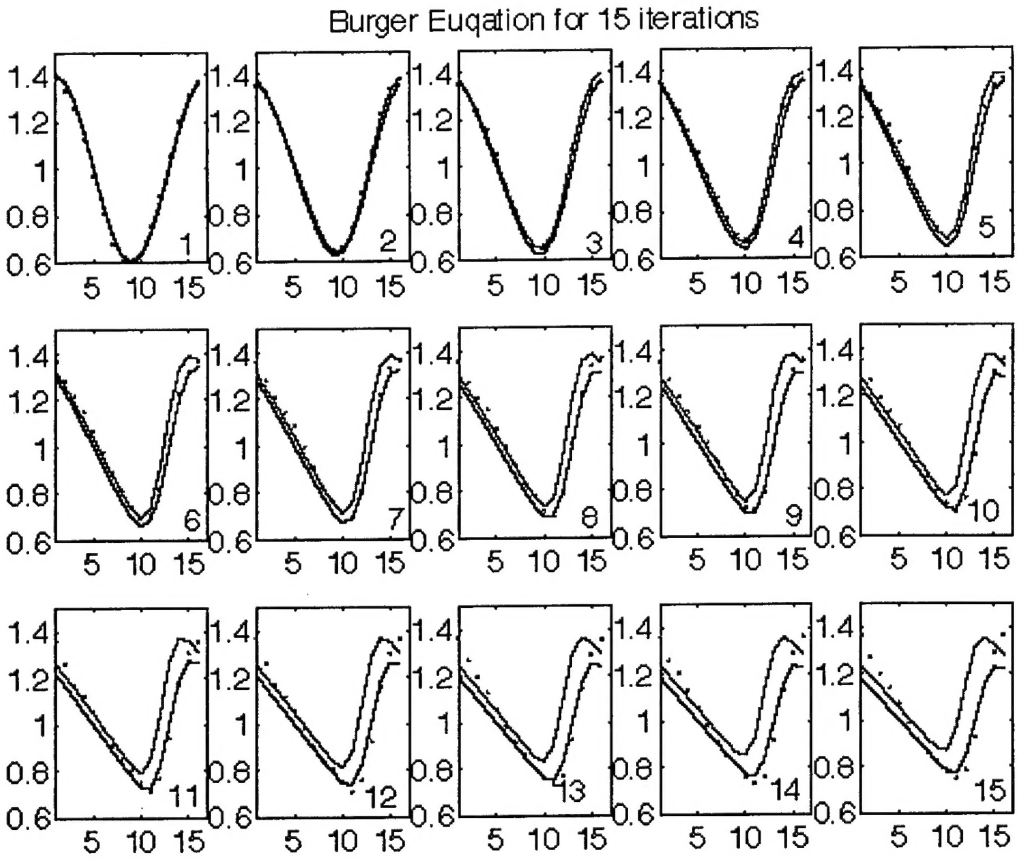


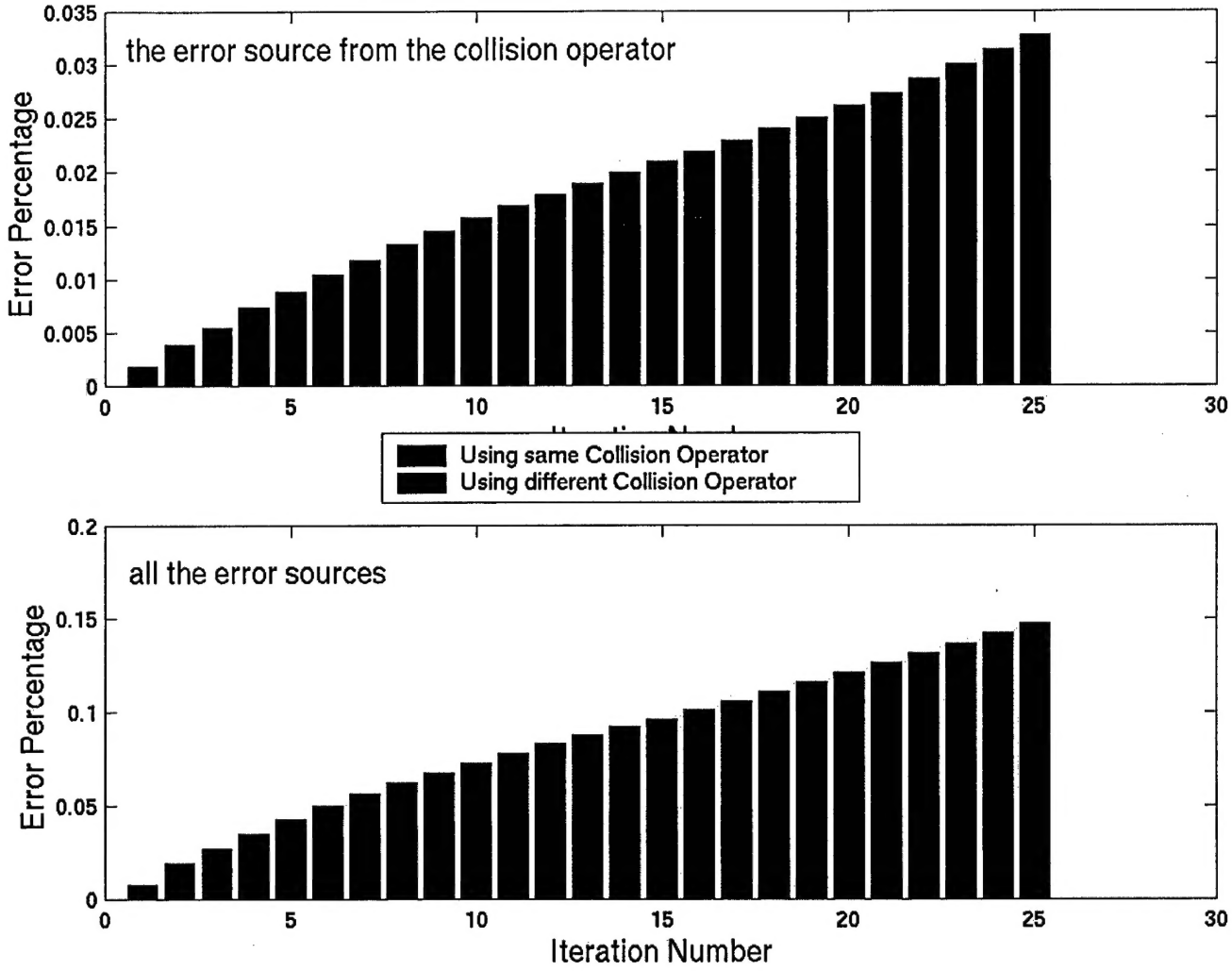
Figure 1: The pulse sequence for the collision operator in the low viscosity case (that is the square root of NOT gate). The two lines in the diagram correspond to RF pulses applying to the proton and carbon qubits. The time delay between the pulses is 1/2J. J is the scalar coupling constant between the H and C nuclear spins.

A critical component of the TTQC approach is to understand how error propagate and to prevent the accumulation of errors from the repeated collision. We investigated this both via a full simulation of the spin dynamics, and through experiments. The simulation uses as its inputs the measured spin Hamiltonian of the molecule (in this case chloroform) and the detailed pulse shapes of the radio-frequency excitations. These are then integrated to recover the dynamics. In general we expect the simulation and experiment to match quite closely. In addition we compute the lattice gas dynamics for the particular equation we are investigating and for the number of cells used. These numerical results are the idealized computation.

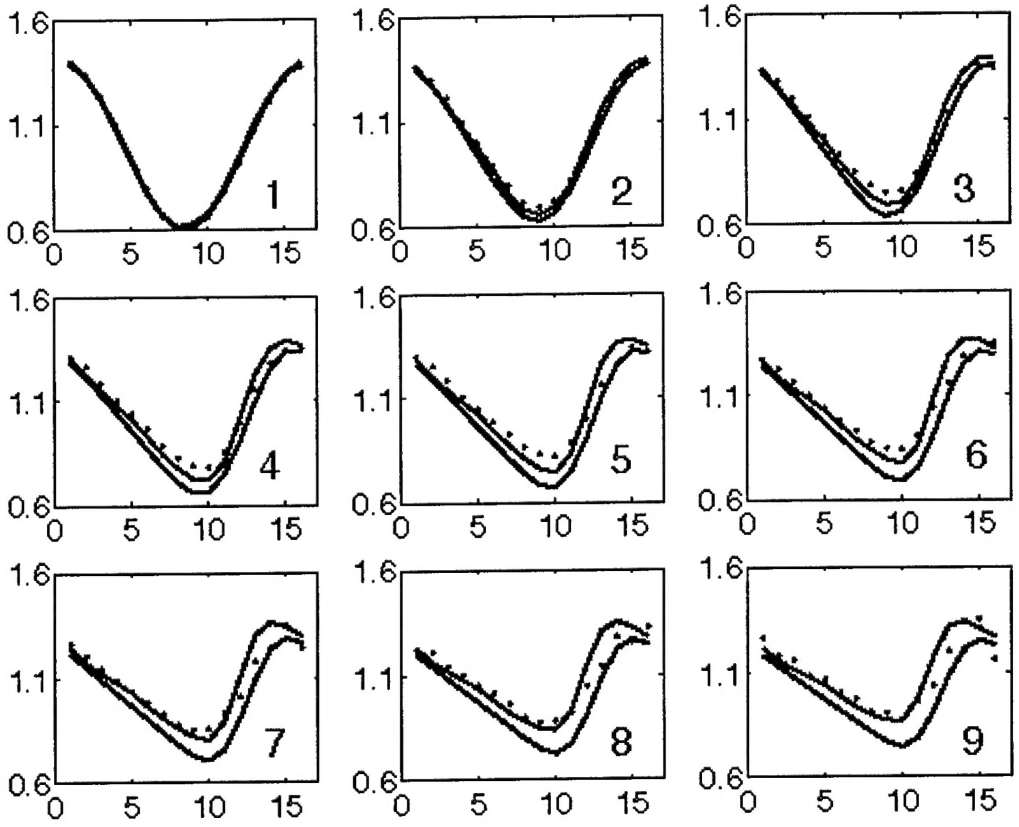


The experimental (dots), numerical/idealized (dark), and simulation of the experiment (light) results for the Burger's equation with 15 iterations. In general the results show that the implementation does return the basic features of the idealized computation and does show a sharpening of the mass density. There is a separation between the idealized and simulated results as expected since the collision operator is only implemented here to first order. That is, there is an intentional small error in the implementation since the collision operator is restricted in time. This is a practical issue of competing with decoherence. This will be explored in more detail in further studies, but in the theoretical, fault tolerant limit this error vanishes.

The surprising feature is that there is a separation between the simulation and the experiment and that the experiment more closely follows the ideal. This latter point we believe to be fortuitous, but the separation between experiment and simulation is important. Part of this arises from the initial conditions, but the key part shows an accumulation of errors from the collision operator. We can see this in the simulations by following the state of the computation through multiple cycles.



The collision operator used here is the square root of NOT gate. The diagram at the top shows only the error of the collision operator. The diagram at the bottom includes all of the error sources. The percentage of error due to the collision operator grows linearly if we use the same pulse sequence over and over, while the error grows only as the square root if we change the phase of the operator each iteration. The introduced here are a simple phase shift of the overall propagator that introduces an unimportant phase into the computation. It is enough to have a systematic rotation of the operator thus introducing a sort of quantum Zeno effect on the overall dynamics.



Above we show the results for the Burger's equation with a higher viscosity and with phase rotation of the collision operator. Here as expected the data more closely follows the simulation.

Although the new console is fully installed we are just starting to use and calibrate it. We expect in the short term it will permit us to implement closed loop control and explore TTQC in 2 and 3 dimensions.

Publications results from AFOSR supported research on TTQC in Professor Cory's Laboratory:

Towards an NMR Implementation of a Quantum Lattice Gas Algorithm, M. Pravia, Z. Chen, J. Yepez and D. G. Cory, *Computer Physics Communications*, 2002, **146**, 339 – 344.

Experimental Demonstration of Quantum Lattice Gas Computation, M. Pravia, Z. Chen, J. Yepez and D. G. Cory, *Quantum Information Processing*, 2003, **2**.